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A DC PROBE FOR ROCKET MEASUREMENTS IN THE IONOSPHERE

L. G. SMITH

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PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON 25, D. C.

JUNE 1963

GEOPHYSICS CORPORATION OF AMERICA BEDFORD, MASSACHUSETTS

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ABSTRACT

The design and use of a D.C. probe for rocket measurements of electron density and electron temperature in the ionosphere is described. The probe is based on the Langmuir probe technique in a form which is particularly suitable for the investigation of features of the ionosphere involving steep gradients, such as Sporadic-E. The potential value of the probe in the D region is indicated.

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NOMENCLATURE

A	probe area
e	electron charge
h	Debye length
i	current
i_e	electron random current
i_+	positive ion random current
j	current density
j_e	electron random current density
j_+	positive ion random current density
k	Boltzmann constant
m_e	electron mass
m_+	positive ion mass
M	molecular weight
n_e	electron density
T_e	electron temperature
T_+	positive ion temperature
v	vehicle velocity
$\overline{v_e}$	electron mean velocity
$\overline{v_+}$	positive ion mean velocity
V	probe potential
V_e	electron energy (volts)
V_f	floating potential
σ	area ratio
η	potential ratio

SECTION 1

LANGMUIR PROBE THEORY

1.1 RETARDING POTENTIAL ANALYSIS

The use of a probe in studying plasmas was originally put on a sound theoretical basis by Langmuir and his colleagues more than thirty years ago.[(1-1)] Experimentally, an electrode is inserted into the plasma and the current to it is determined as a function of the potential of the electrode. From the resulting current-voltage characteristic the electron energy distribution and the electron density are obtained.

When the electrode is exactly at the potential of the plasma the electron current to it is determined by the random thermal motions of the electrons in the gas. From kinetic theory the number of electrons striking unit area per second is $n_e\overline{v_e}/4$ where n_e is the electron density and $\overline{v_e}$ the mean electron velocity. Since each electron carries a charge e, the electron random current density j_e is given by

$$j_e = n_e e \, \overline{v_e}/4 \qquad (1\text{-}1)$$

The mean electron velocity $\overline{v_e}$ is related to the electron temperature T_e by

$$\overline{v_e} = (8kT_e/\pi m_e)^{\frac{1}{2}} \qquad (1\text{-}2)$$

where k is the Boltzmann constant and m_e is the electron mass. The use here of electron temperature implies a Maxwellian distribution, i.e., thermal equilibrium. Numerically,

$$\overline{v_e} = 6.21 \times 10^5\ T_e^{\frac{1}{2}}\ \text{cm/sec} \qquad (1\text{-}3a)$$

or

$$\overline{v_e} = 6.69 \times 10^7\ V_e^{\frac{1}{2}}\ \text{cm/sec} \qquad (1\text{-}3b)$$

where V_e is the electron energy in volts.

The variation of electron random current density as a function of electron density is shown in Figure 1-1 for three values of electron energy.

As the electrode is made negative with respect to the plasma, only those electrons with energies greater than the retarding potential can strike the electrode. For retarding potentials the electron current density j is given by

$$j = j_e \exp(eV/kT_e) \qquad (1\text{-}4)$$

where V is the retarding potential.

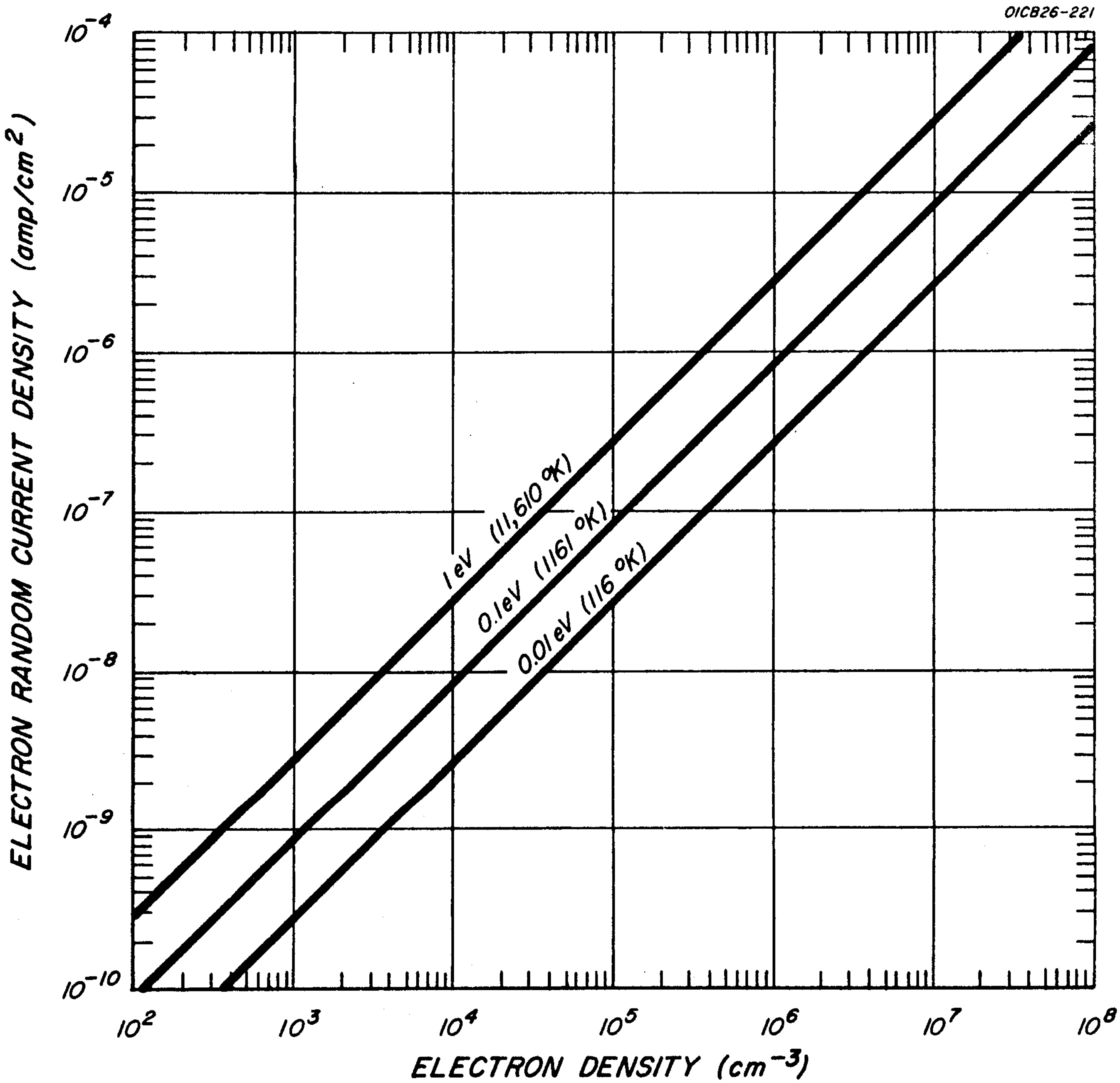

Figure 1-1. Electron random current density as function of electron density for three values of electron energy.

Equations (1-1), (1-2) and (1-4) above, define the theory of the Langmuir probe technique in its simplest possible terms.

1.2 PLASMA SHEATH

Important to the basic theory of the Langmuir probe, though not appearing explicitly in the formulae quoted above, is the concept of the plasma sheath--the space charge region adjacent to the electrode. It will be realized that the sheath has zero thickness (i.e., does not exist) when the electrode is at plasma potential. The concept of the sheath is important in two respects: (1) it provides a criterion for the validity of the technique; namely, that the mean free path be large compared with the sheath thickness, and (2) it provides a method of computing the current-voltage curves for accelerating potentials. Such calculations have been given in detail by Mott-Smith and Langmuir.[1-2]

The thickness of the plasma sheath varies with the potential of the electrode, but the scale of thickness can conveniently be expressed in terms of the plasma properties by the Debye shielding length h, defined by the equation

$$h = \left(\frac{kT_e}{4\pi\, n_e e^2}\right)^{\frac{1}{2}} = 6.90\ (T_e/n_e)^{\frac{1}{2}}\ \text{cgs units} \qquad (1\text{-}5)$$

The variation of Debye shielding length with electron density is shown in Figure 1-2 for three values of electron energy.

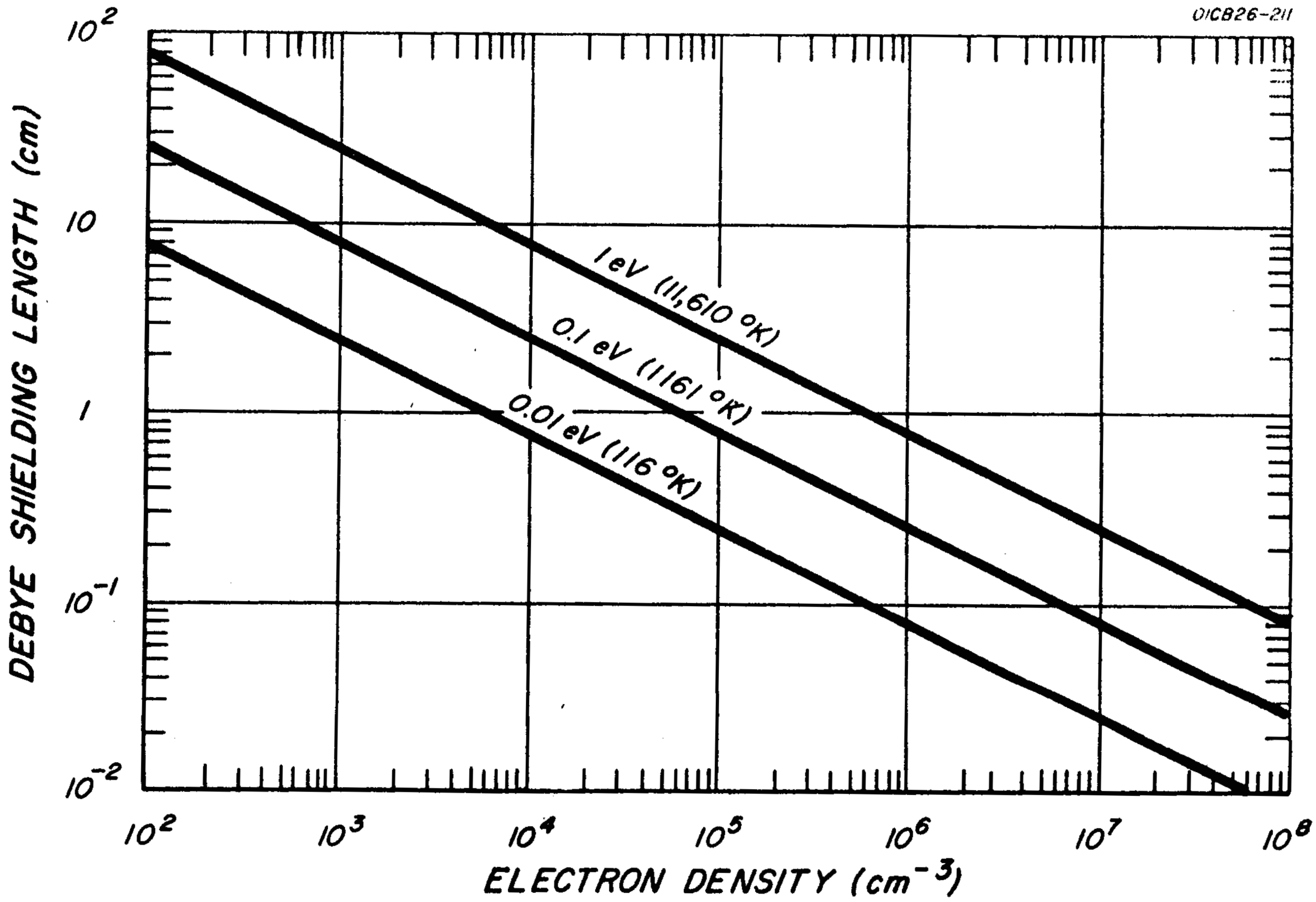

Figure 1-2. Debye shielding length as a function of electron density for three values of electron energy.

The current-voltage characteristic for accelerating potentials is a function of the shape and size of the electrode. Exact expressions are available when the dimensions of the electrode are very large or very small compared with the Debye shielding length:

(1) Large plane

$$j = j_e \tag{1-6}$$

(2) Long thin cylinder

$$j = j_e \left\{ \frac{2}{\pi^{\frac{1}{2}}} \left(\frac{eV}{kT_e} \right)^{\frac{1}{2}} + \exp \left(\frac{eV}{kT_e} \right) \mathrm{erf} \left(\frac{eV}{kT_e} \right)^{\frac{1}{2}} \right\} \tag{1-7}$$

(3) Small sphere

$$j = j_e \left(1 + \frac{eV}{kT_e} \right) \tag{1-8}$$

A normalized semi-log plot of electron current versus voltage is shown in Figure 1-3 for these three electrode configurations. The large plane and small sphere are limiting cases; all other electrode shapes result in plots falling within the region between these two curves. As noted before, for retarding potentials the current density is independent of electrode shape and the semi-log plot results in a straight line where slope gives the electron temperature. The point at which the electrode is at plasma potential is readily identified by the change in slope on this semi-log plot.

1.3 NON-MAXWELLIAN ENERGY DISTRIBUTION

When the electron energy distribution is not Maxwellian the log j-V plot is not linear in the retarding potential region. The

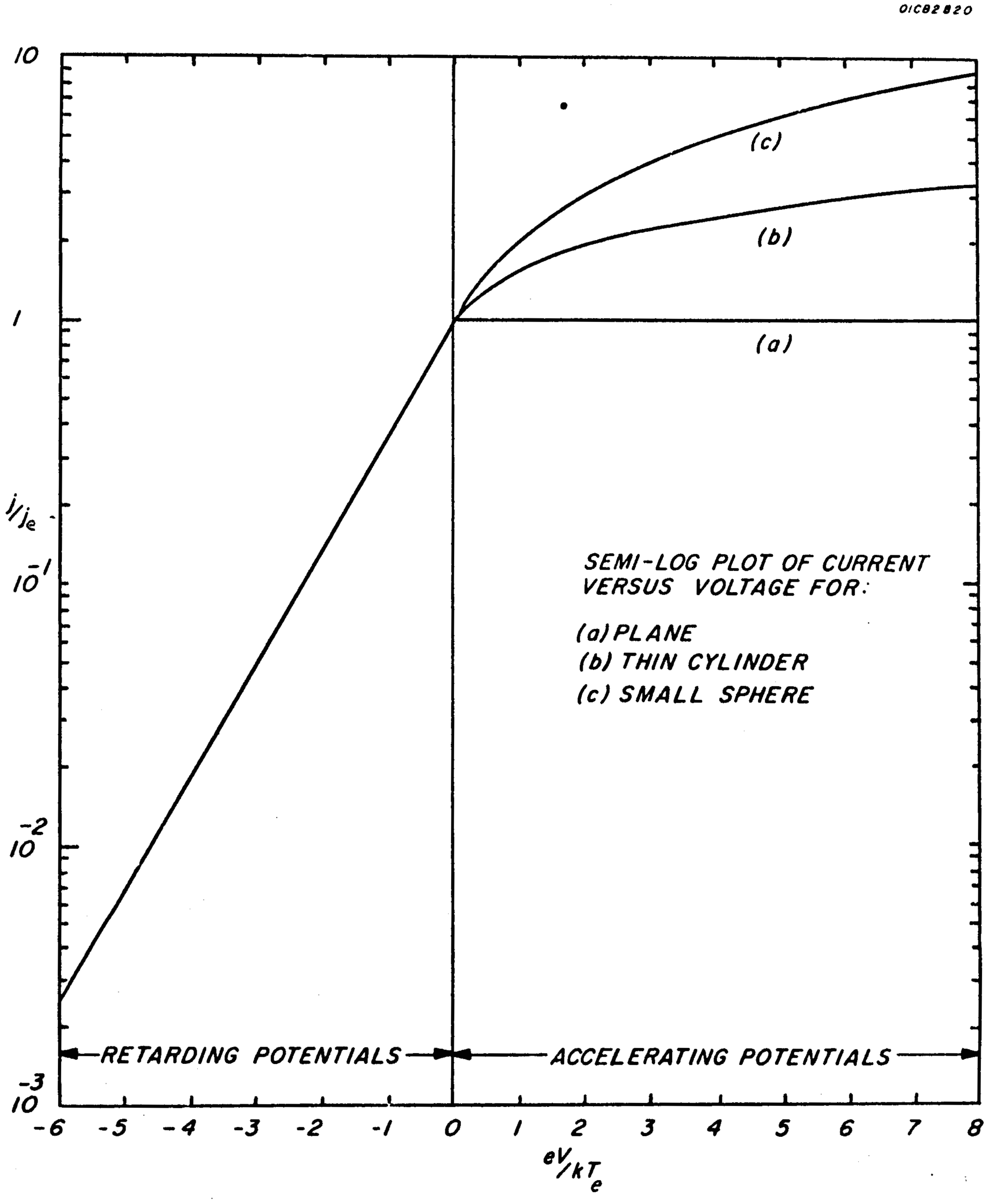

Figure 1-3. Theoretical semi-log plot of electron current.

current-voltage curve may still be analysed, however, to give the actual electron energy distribution. A convenient method, due to Druyvesteyn,(1-3) uses the second derivative d^2j/dV^2. Expressed in terms of the electron energy in volts, V_e, the distribution function $F(V_e)$ is given by

$$F(V_e) = \frac{1}{n}\frac{dn}{dV_e} = \frac{(8m)^{\frac{1}{2}}}{e^{3/2}} V^{\frac{1}{2}} \frac{d^2j}{dV^2} \qquad (1\text{-}9)$$

Several methods are available for obtaining the second derivative electrically though only recently has the theory of such methods been discussed generally.(1-4) The automatic technique was not incorporated in the instrument described in this report.

1.4 POSITIVE ION CURRENT

The current to the electrode is the sum of currents due to positive ions as well as electrons. (Here and later we postulate the absence of negative ions.) The positive ion component of the current is given by Equations (1-1), (1-2) and (1-4) when the sign of the potential is reversed and j_+, T_+, $\overline{v_+}$ and m_+ are substituted for the corresponding quantities j_e, T_e, $\overline{v_e}$ and m_e. Because of the much greater mass of the positive ion (for atomic oxygen $m_+/m_e = 16 \times 1836$), the positive ion random current density is smaller than the electron random current density by a factor of about 170. This has two important consequences: (1) correcting the observed current to obtain the electron current involves a small quantity, and (2) because the ion current is small it is not practical to use the technique to obtain positive ion densities and temperatures.

1.5 FLOATING POTENTIAL

The potential at which the total electrode current is zero is of considerable significance in rocket and satellite measurements. This is a negative potential V_f known as the floating (or wall) potential, because any isolated conductor or insulator will come to this potential under electron and positive bombardment. Since the positive ion and electron currents must be equal in magnitude, the value of V_f is given by

$$j_+ = j_e \exp\left[-(eV_f/kT_e)\right]$$

or

$$eV_f = kT_e \log_e (j_e/j_+) = 5.1\ kT_e$$

for $(j_e/j_+) = 170$. Thus the floating potential is almost equal to five times the electron energy when both are expressed in volts. This value is very insensitive to the particular values assumed for ion mass and ion temperature.

1.6 BI-POLAR PROBE

An important development of the Langmuir probe technique is known as the floating double-probe method.[1-5] Two probes are inserted in the plasma and the current flowing between them is measured as a function of the voltage difference without reference to the actual potential of the plasma. The method was originally developed to minimize the reaction of the probes on the plasma under investigation. It is also used on rockets and satellites where no reference potential is available.

The two probes comprising the bi-polar arrangement are not necessarily equal in size or shape. If the inequality in size of the two probes is considerable then the smaller can be treated as a single probe, the other providing a constant reference potential. An analysis of the current-voltage characteristic as a function of the area ratio (σ) is given in the appendix.

Three modes of operation of a bi-polar probe are determined by the magnitude of the area ratio of the probes σ and the ratio of electron to ion random current density j_e/j_+:

(1) $1 \leqslant \sigma < j_e/j_+$. In this mode of operation neither probe can be driven positive with respect to the plasma. Hence the electron random current density is not measured. In addition the value of electron temperature that is obtained is representative of these electrons with energies greater than a certain value. There is very little to recommend this mode of operation.

(2) $j_e/j_+ \leqslant \sigma < 10\ j_e/j_+$. Electron and ion random current densities are measured. The electron temperature is obtained for a complete spectrum of electron energies and it is possible to test for a Maxwellian distribution.

(3) $10j_e/j_+ \leqslant \sigma$. The merits of the previous mode are present with the advantage that the data evaluation is somewhat simplified. It has the disadvantage that, for a given total probe area, the probe current is rather small.

The optimum area ratio for the bi-polar probe is considered to be $\sigma = 10j_e/j_+$.

Another result of this analysis is that the value of electron temperature that is obtained is not affected by the area ratio of the electrodes.

1.7 LIMITATIONS OF PROBE THEORY.

There are restrictions on the use of the Langmuir probe. The following criteria must be met when applying the probe to the study of discharges in gases:

(1) The probe dimensions must be small in comparison to significant changes in potential over the space it occupies.

(2) The current drawn by the probe must not disturb the plasma.

(3) There must be no collisions within the sheath (i.e., the mean-free path must be large compared with the sheath thickness).

(4) There must be no production of electrons by impact, photoemission, etc., at the probe surface.

(5) Contact potential differences must be constant.

(6) Radio-frequency fields must be absent (because of the possibility of exciting plasma oscillations).

(7) The geometry of the probe arrangement must be clearly defined.

Within the limitations imposed by these criteria, the Langmuir probe has proved an elegant and powerful tool for the study of low pressure discharges. Attempts have been made to extend the use of the probe to other conditions, particularly to higher pressures, (i.e., short mean free paths) but the interpretation under these conditions is uncertain.

SECTION 2

THE PROBE IN THE IONOSPHERE

2.1 USEFUL ALTITUDE RANGE

The ionosphere in the E region provides an almost ideal plasma for application of the Langmuir probe technique. Values of some of the relevant quantities are given in Table 2-1. The theory of the probe is invalid at heights below about 90 km because two important factors do not meet the criteria previously given: (1) the mean free path is not large compared with the Debye length and (2) negative ions are present in significant numbers.

The use of the probe in the F region is limited by photoemission. The photoelectric current density from a tungsten surface exposed to unattenuated solar radiation is about 4×10^{-9} amp/cm^2. This is equal to the random current for a value of electron density of about 4×10^3 cm^{-3} (at a temperature of $10^{3\,\circ}$K). This gives an upper limit to the height range for daytime measurements of about 1000 km.

TABLE 2-1

SELECTED QUANTITIES RELEVANT TO THE LANGMUIR PROBE IN THE IONOSPHERE

Height, h Km	150	250	350	700
Electron Concentration, n_e cm^{-3} (noon)	2×10^5	1×10^6	2×10^6	2×10^5
*Temperature, T^oK	1031	1415	1445	1812
Molecular Weight, M (ions)	28	16	16	16
Ratio, $\overline{v_e}/\overline{v_+}$ $(= j_e/j_+)$	228	170	170	170
Electron Mean Velocity, $\overline{v_e}$ cm sec^{-1}	2.0×10^7	2.3×10^7	2.4×10^7	2.7×10^7
Ion Mean Velocity, $\overline{v_+}$ cm sec^{-1}	8.8×10^4	1.4×10^5	1.4×10^5	1.6×10^5
Electron Random Current Density, j_e amp cm^{-2}	1.6×10^{-7}	9.2×10^{-7}	1.9×10^{-6}	2.1×10^{-7}
Ion Random Current Density, j_+ amp cm^{-2}	7.0×10^{-10}	5.4×10^{-9}	1.1×10^{-8}	1.2×10^{-9}
Floating Potential, V_f volt	-0.48	-0.63	-0.64	-0.80
Debye shielding length, h cm	0.50	0.26	0.19	0.66

*Values up to 700 km from 1959 ARDC Model Atmosphere

2.2 ENVIRONMENT OF THE VEHICLE

The atmosphere in the vicinity of a rocket or satellite is disturbed from its quasi-equilibrium state. The electron density, probably more than any other property, is susceptible to considerable modification. If a probe is to succeed in measuring ambient electron density it is of the utmost importance that the interaction of the vehicle and the ionosphere be understood. Considered to be of potential importance are:

(1) Ionization by R. F. excitation, increasing the electron density.

(2) Absorption of R. F. energy, increasing the electron temperature.

(3) Rectification at the antennas, modifying the vehicle potential.

(4) Escaping gas and outgassing, tending to dilute the plasma.

(5) Vehicle motion, modifying the spatial density distribution.

(6) Shock wave ionization, increasing the electron density.

(7) Photo emission from the vehicle, modifying the vehicle potential.

(8) Magnetic fields (including the geomagnetic field) modifying the probe current.

Effects associated with the R. F. transmitters, when, as usually is the case, the data is telemetered, with gas contaminating the environment and with vehicle motion can, in practice be made negligible by suitable design of the experiment. Photoemission (in daytime) and the geomagnetic field are left as being inherent limitations on a probe measurement of electron density. The theory of operation of the probe should be modified to incorporate these effects.

2.3 VEHICLE MOTION

It is in the nature of rocket and satellite-borne instruments they are moving with significant velocity relative to the plasma. It is important to consider the effect of this relative motion on the operation and interpretation of the probe. Two separate aspects of the motion can be distinguished.

2.3.1 Effect of Motion on Ion Current.

The velocity of a sounding rocket (say 1 km/sec) is comparable with, and the velocity of a satellite (say 8 km/sec) is appreciably greater than, the mean velocity of the ions (of the order of 1 km/sec), although both are very small compared with the mean velocity of electrons (about 200 km/sec). The ion current to an electrode is increased due to relative motion whereas the electron current is not appreciably changed. An exact expression has been given by Sagalyn, Smiddy and Wisnia[(2-1)] for a spherical electrode. This is shown graphically in Figure 2-1. When the vehicle velocity, v, equals the mean ion velocity, $\overline{v_+}$, the current is increased about 40 percent above the value with no relative motion. For a satellite having a velocity of 8 times the mean ion velocity the current is increased by a factor of about 8. Since the ion current is still small compared with the electron current the motion of the vehicle does not affect the retarding potential analysis for electrons.

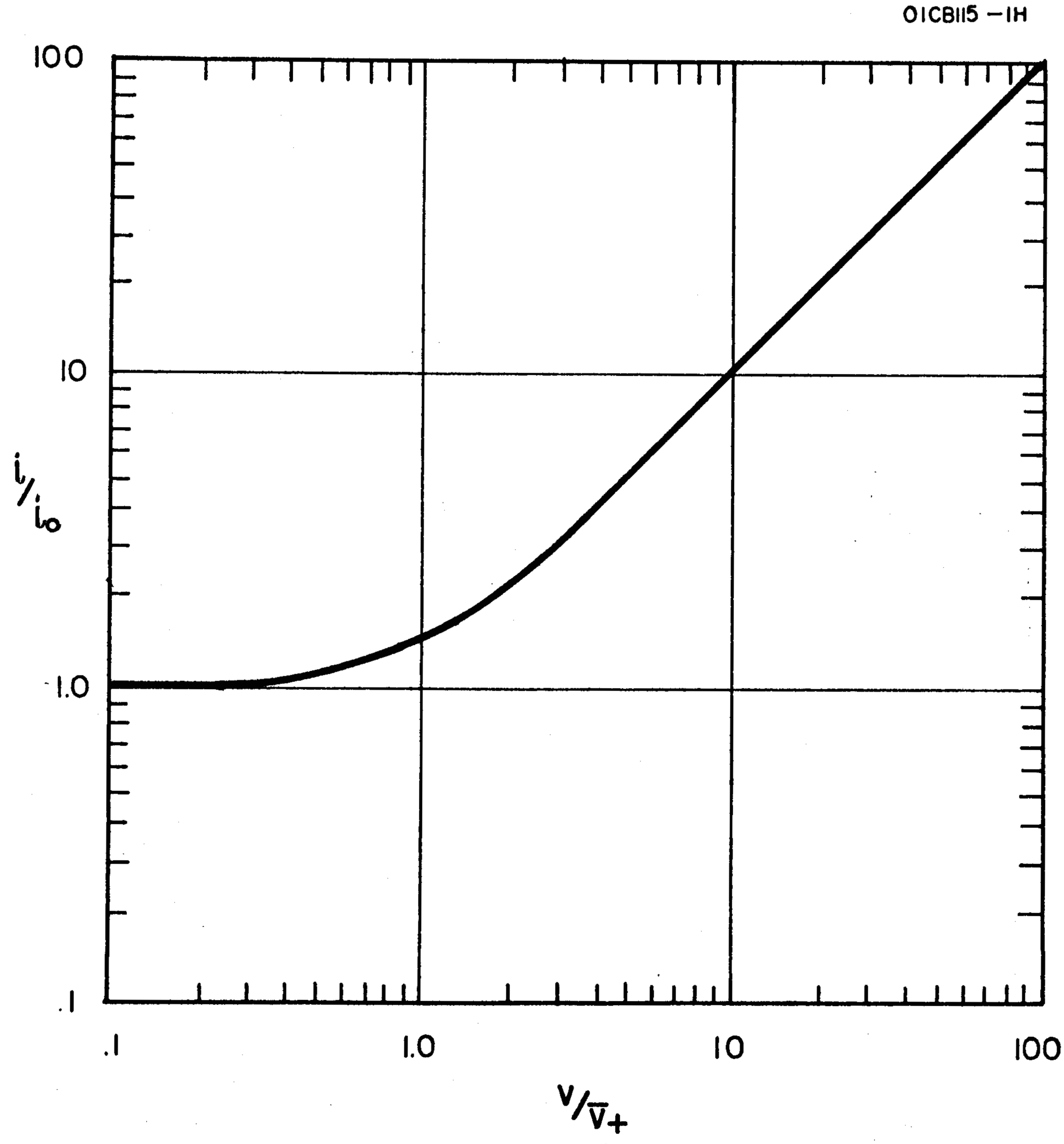

Figure 2-1. Effect of vehicle velocity on ion current.

2.3.2 Rarefaction in the Vehicle Wake. A further factor affecting the design of a probe experiment results from the local disturbance of ion and electron density due to rarefaction in the wake of a body traveling through the plasma with a velocity comparable with or greater than the mean ion velocity.(2-2) Although the electrons have sufficient velocity individually to penetrate this region the absence of a neutralizing positive space charge prevents the build up of an appreciable electron concentration with the result that the electron density distribution also shows a rarefaction in the wake of the vehicle. This effect showed up clearly in an early flight (Nike-Cajun 10.25) which included in the payload an electrode in the form of a disc flush-mounted in the cylindrial section of the payload housing. This rocket slowly executed a large precession cone while spinning more rapidly on its longitudinal axis. It was found that the current to this probe was modulated in synchronism with the spin, being a minimum with the electrode at the trailing side of the payload. The probe on a rocket or satellite should therefore be located so as to minimize the probability of its passage through the rarefied vehicle wake.

2.4 MAGNETIC FIELD

A factor which is not considered in simple probe theory is the effect of a magnetic field. In the E region the radius of gyration (Larmor radius) for electrons in the geomagnetic field is about 1 cm. Since this dimension is less than the mean free path of the electrons and comparable with the size of the probe normally used, the motions of electrons into or away from the probe must be profoundly affected.

In some unpublished lecture notes F. F. Chen states that in a magnetic field weak enough that the ion Larmor radius is large compared with the probe radius and the Debye length and hence that j_+ is not affected, but strong enough that the electron Larmor radius is comparable to or smaller than the relevant dimensions, the ratio j_e/j_+ falls to 10 or 20. In the absence of a magnetic field the ratio j_e/j_+ has a value of about 200. Thus the geomagnetic field would tend to decrease the observed value of j_e by an order of magnitude. There is some evidence that this is the case. Chen also states that, in the presence of a weak magnetic field the retarding potential analysis would not be affected and the resulting value of electron temperature should be correct. It should be pointed out however, that there exists no comprehensive mathematical treatment of the Langmuir probe theory in the presence of even a weak magnetic field. This is of no particular concern in respect of the use of the probe to measure electron density where other methods (such as radio-frequency techniques) can be used to check and calibrate the equipment. There is no direct method of measuring electron temperature, however, which is not based on Equation (1-4).

2.5 MEASUREMENT OF IONOSPHERIC IRREGULARITIES

An important aspect of probes carried by rockets and satellites is their ability to resolve the fine structure of the medium. This is most important initially in respect to electron density where less direct methods, e.g., radio star scintillations, have indicated that significant variations exist having typical dimensions as small as 200 meters.

A basic weakness of the conventional Langmuir probe technique is its poor time resolution. This follows because a complete sweep of potential of the electrode leads to only a single value of electron density and of electron temperature. In practice, the sweep duration is limited by two factors: (1) a bandwidth of the measuring device, and (2) the bandwidth of the telemetry system. A sweep duration of the order of one second is generally convenient for rocket and satellite measurements although this can be reduced to about 0.1 sec at the expense of elaborating the instrument. However, an alternative method has been developed and used with considerable success.[2-3]

The method is experimentally very simple but somewhat more difficult to justify on theoretical grounds. It consists in changing the program of the voltage applied to the probing electrode from one of consecutive sweeps to a program in which occasional sweeps are separated by periods of fixed voltage. In recent flights using the technique, the program consists of a sweep voltage of -2.7 to +2.7 volt (duration 0.5 sec) alternating with a fixed voltage of +2.7 volt (duration 1.5 sec), Figure 2-2.

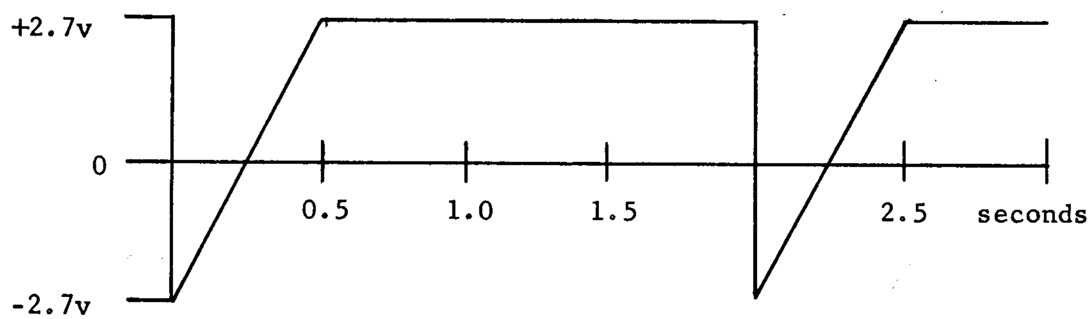

Figure 2-2. Probe Voltage Program.

The probe current at fixed potential is proportional to electron density. The only assumption made is that electron temperature is constant; the current is proportional to the average velocity of the electrons and hence varies as $(T_e)^{\frac{1}{2}}$. The proportionality of current to electron density has been verified in the flight of a rocket (Nike-Apache 14.31) which carried a D.C. probe and a C.W. propogation experiment, the latter prepared by S. J. Bauer.

The distance resolution of the instrument used in this way depends on the vehicle velocity and the bandwidth of the system (including telemetry). For a rocket with a velocity of 1 km/sec and a bandwidth of 1 kc/sec the distance resolution is 1m, more than adequate for present applications. In a satellite having a velocity of 8 km/sec the bandwidth required to give a distance resolution of 80m would be 100c/sec.

2.6 TELEMETRY REQUIREMENTS

The bandwidth required in the telemetry channel is principally determined by the lower limit of electron temperatures. In the lower E region values of electron temperature as low as $300^{\circ}K$ have been measured and it is probably desirable that the limit for the measurement be set at $100^{\circ}K$. This corresponds to a mean electron energy of about 0.01 volt. Now the sweep voltage applied to the probe has a slope of 10 volts/sec which is equal to an increment of 0.01 volt in 1 msec. This indicates that the bandwidth should be about 1 kc/sec if the exponentially rising current in the retarding potential region is to be transmitted.

The output of the instrument is an analog voltage and may be transmitted by any standard telemetry system. It has been found that the FM/FM system is the most convenient manner of telemetering for this instrument when used on sounding rockets.

2.7 CONTACT POTENTIAL

A feature of the current-voltage plots obtained on rocket flights using the bi-polar arrangement is that they do not pass through the origin of coordinates. Thus with zero potential applied to the electrode (either nose or side) the current is not zero. Similarly the electrode must be made positive with respect to the rocket body to reduce the probe current to zero. Comparison of actual and theoretical plots shows that the curve is displaced along the voltage axis rather than the current axis. Thus the effect is due to a bias voltage appearing in the probe circuit. This bias voltage usually lies between 0.5 and 1.0 volt and may change slowly with time, Figure 2-3.

The bias is believed to be an effect produced by contact potential though no complete explanation can be given. It has been observed in laboratory tests that, while there is no bias voltage when an ohmic (carbon) resistor is used as a load, the bias appears when a very dilute solution of common salt is used. This was also noticed on one occasion (Nike-Cajun 10.108) the bias voltage appeared as salt spray accumulated on the rocket during the pre-launch period. (Incidentally, the leakage current due to the salt spray disappeared at launch).

The contact potential presumably arises from the use of dissimilar metals for the two electrodes of the bi-polar arrangement. The change during flight is believed to be due to the heating of the electrodes during the launch phase.

The actual value of the contact potential is of no consequence in the normal retarding potential analysis since the potentials are automatically referred to plasma potential. It does, however, somewhat affect the fixed-voltage mode of operation of the probe since any change in contact potential produces an equal change in the potential of the probe with respect to the plasma. When this effect is important a correction may be obtained from the individual current-voltage plots.

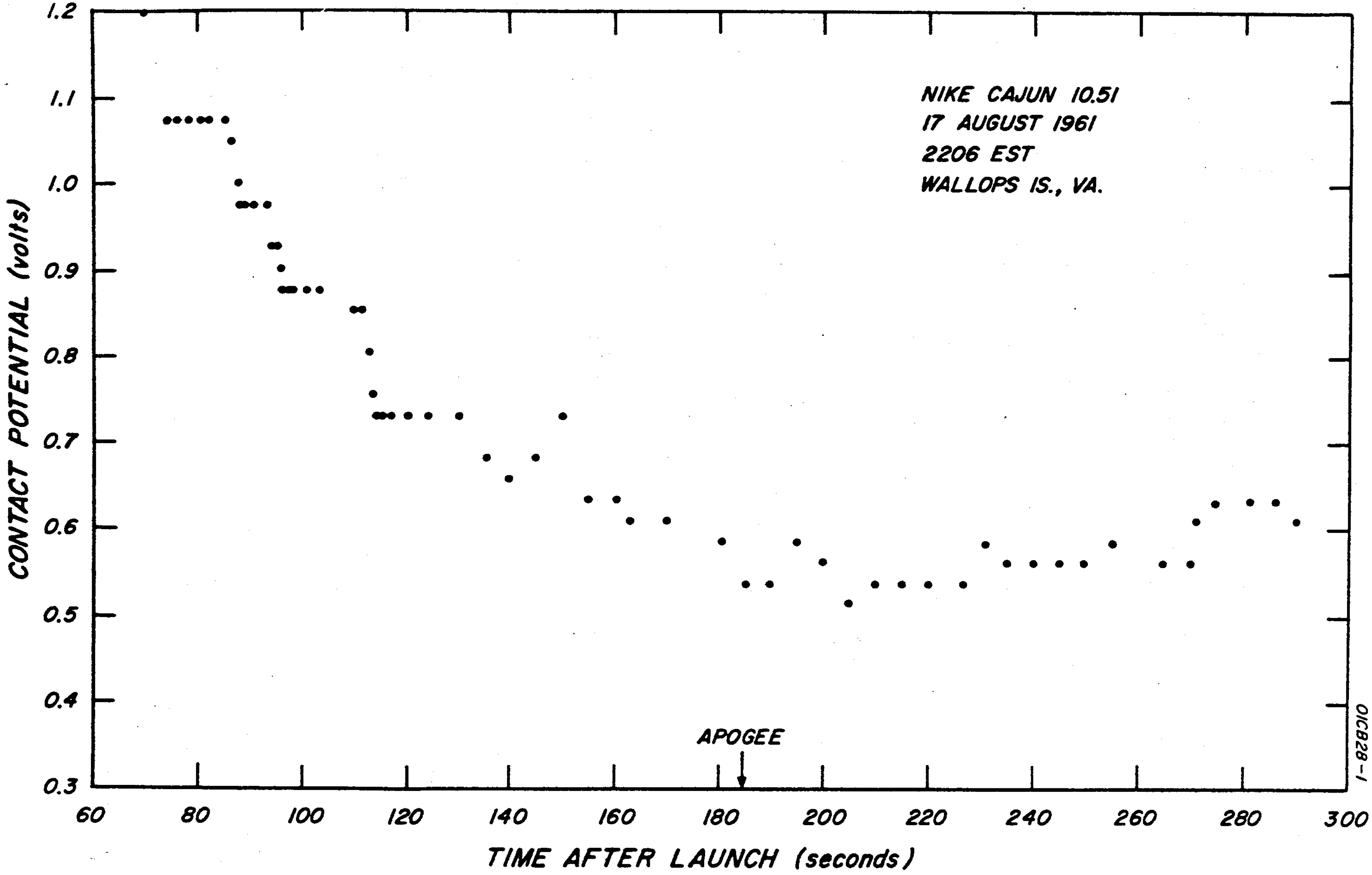

Figure 2-3. Variation of contact potential.

2.8 PROBE IN THE D REGION

In daytime flights probe current is first measured at about 50 km and at night at about 75 km. Profiles obtained on four recent flights are shown in Figure 2-4. Nike-Cajun 10.99 was a pre-dawn flight into a quiet ionosphere with sporadic E present (the bifurcated layer between 98 and 102 km). Nike-Cajun 10.108 was also a pre-dawn flight but into a disturbed ionosphere (indicated by the ionosonde). Nike-Cajun 10.109 was launched at sunset into a quiet ionosphere with sporadic E present (possibly the peak at 110 km). Nike-Apache 14.86 gave a typical daytime profile.

The proportionality of probe current to electron density can be justified on theoretical grounds at heights greater than 90 km. The general appearence of these profiles, however, strongly suggest that this proportionality is also true in the lower portions of the profiles. In the daytime profile the so-called C layer may be identified between 50 and 65 km with the peak at 58 km. The D layer, occurring between 65 and 82 km, corresponds with the absorption of Lyman-α radiation. The nighttime profiles show a generally steeper gradient. Pending further analysis of the operation of the D.C. probe and possible comparison with independent techniques the profile of probe current should be taken to indicate the type of structure that prevails in the D region and the values of electron density disregarded.

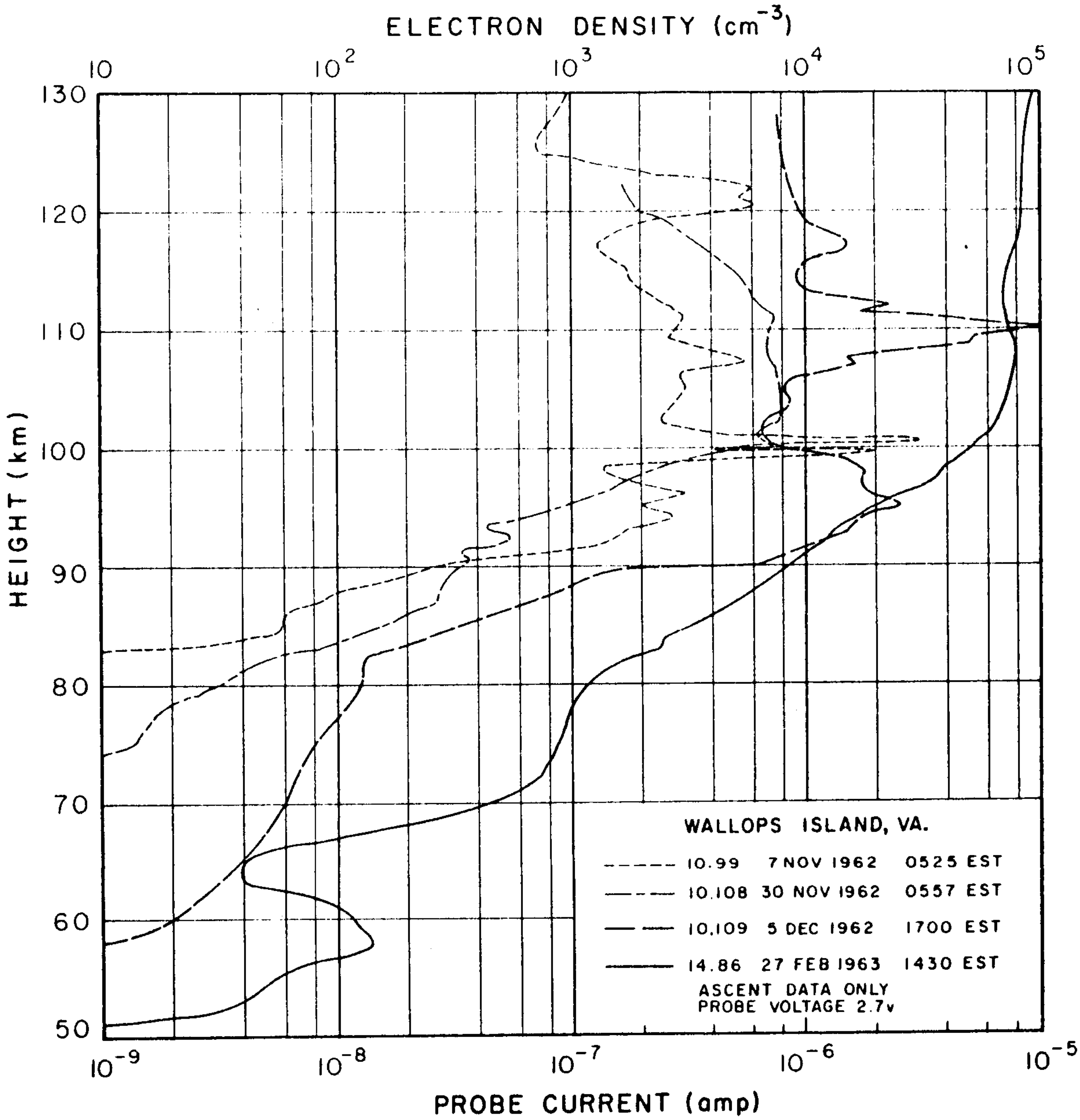

Figure 2-4. Profiles of probe current in the D and lower E region.

SECTION 3

INSTRUMENTATION

3.1 GENERAL ARRANGEMENT

The instrument has been constructed in several models differing in detail but with the same basic circuit arrangement. The instrument has been used most frequently with the nose tip of the rocket as the probing electrode. This may be seen in Figure 3-1 which shows the payload of Nike-Cajun 10.52. The circular electrode on the side of the payload was found to be unsatisfactory and was not used on subsequent flights. Otherwise the external configuration has remained the same. The probe instrumentation occupies the top three decks visible in the figure while the lower part of the instrumentation rack is used for power supplies and telemetering equipment. The upper encapsulated section contains two magnetic aspect sensors.

A different version of the instrument was build to be flown in the nose of an Aerobee. The unit, shown in Figure 3-2 with the heat shield removed from the upper section (program unit), was flown on Aerobee 4.48. The basic method of construction has been retained in subsequent flights of Nike-Apache rockets.

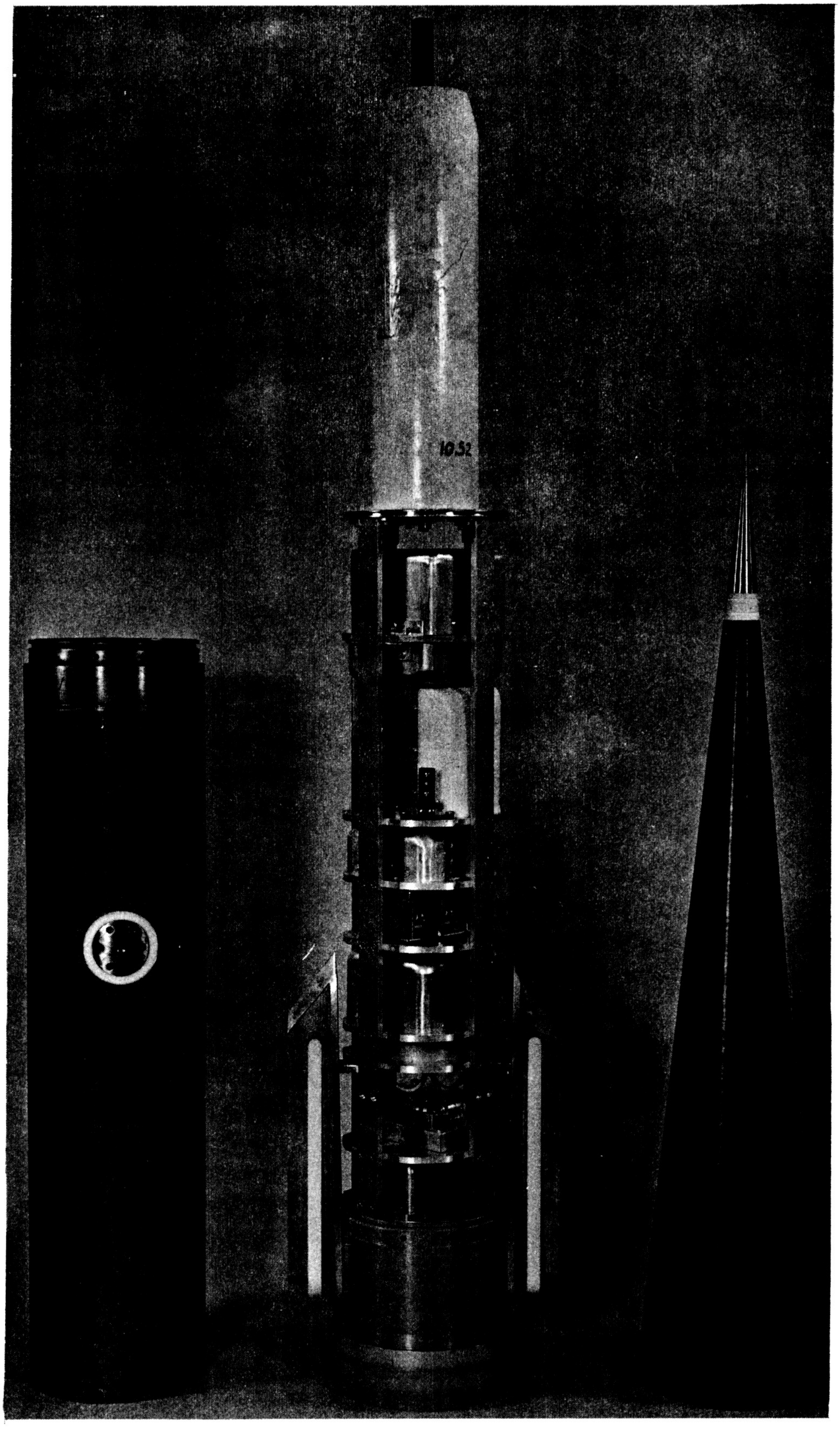

Figure 3-1. Payload of Nike-Cajun 10.52.

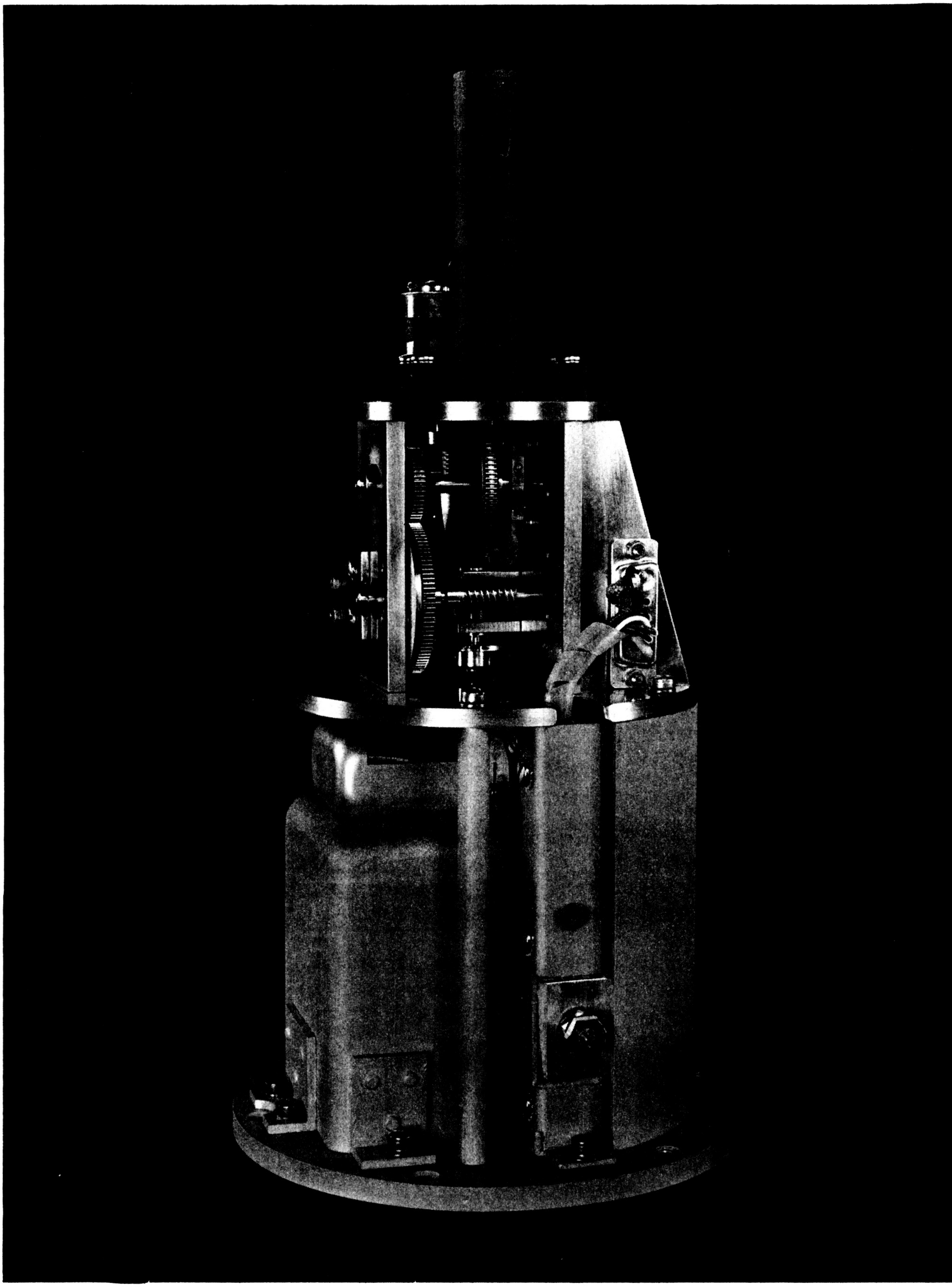

Figure 3-2. Instrument with heat shield removed.

The basic circuit of the probe is shown schematically in Figure 3-3. The two main parts are the electro-mechanical program unit and the electrometer. The program unit is so called because it creates the voltage function applied to the probe. The electrometer converts the probe current to an analog voltage which is the output of the instrument.

The program unit forms the upper part of the complete instrument which is constructed in modular form. The lower part contains a central wiring channel to which four sub-assemblies are attached: the program unit from the top, the electrometer from the front and, from the back, the battery box and the unit containing the thyrite resistor and the calibration resistor. The diameter of the base is 5-1/2 in. and the height 8-1/2 in. The unit can be installed inside a cone having a 6-1/2 in. diameter at the base and a 20° included angle. The weight of the complete instrument is 5 lb.

The instrument is normally used with a conical electrode having an included angle of 11° or 20°. The construction in either case is the same and is shown in Figure 3-4 for an 11° cone. The electrode assembly replaces the standard nose tip and therefore does not add extra weight to the payload. Electrical connection is made through the rod which mates with a special connector on the instrument and allows a limited amount of relative motion (such as results from thermal expansion of the payload housing).

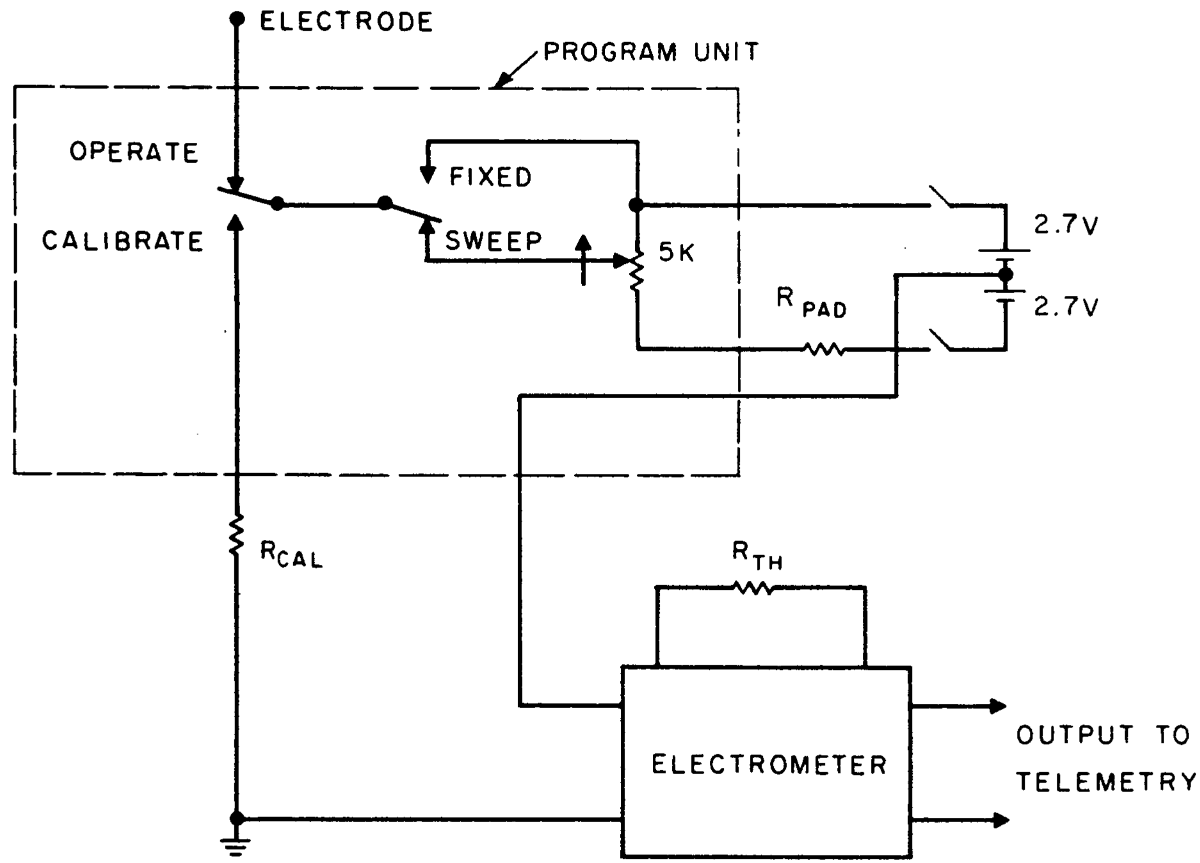

Figure 3-3. Probe circuit schematic.

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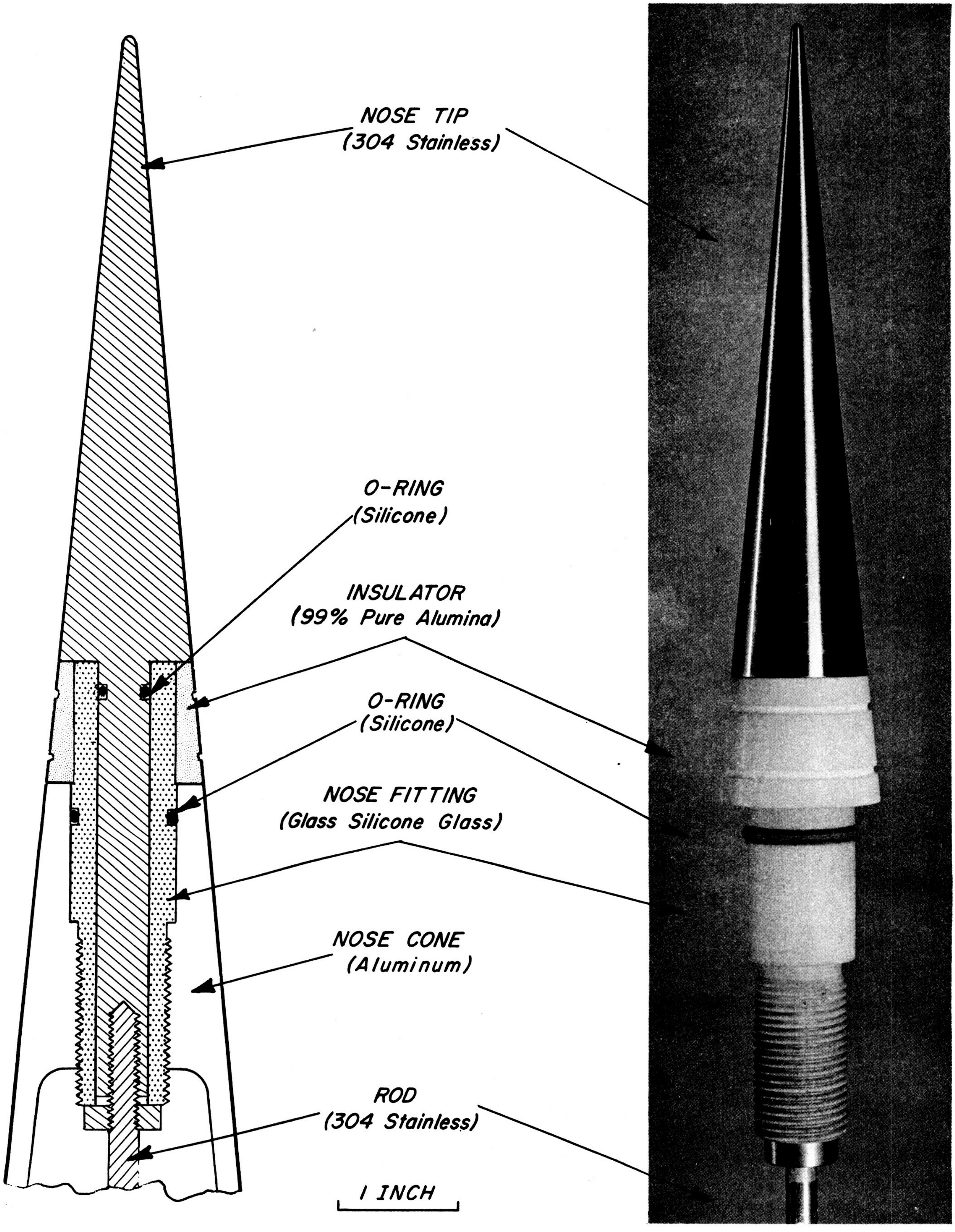


Figure 3-4. Nose tip electrode.

3.2 PROGRAM UNIT

The program unit serves three main functions:

(1) Sweep generator. A linear potentiometer (5k ohm) is driven in continuous rotation at about 2 rps.

(2) Mode Switching. A cam-operated microswitch alternates the mode of operation between a single sweep (-2.7 volts + 2.7 volt, duration 0.5 sec) and a period of fixed voltage (+2.7 volt, duration 1.5 sec).

(3) Calibration. A second cam-operated microswitch inserts a fixed resistor in place of the probe at intervals of 20 seconds for the duration of a single sweep.

The construction of the program unit in the most recent instruments is shown in Figure 3-5. A dc motor (Globe Industries, No. 41A345) with a shaft speed of 100 rps drives the potentiometer at 2 rps. This is followed by the mode-switching cam (#1) at 1/2 rps and the calibration cam (#2) at 1/20 rps. In some applications a commutator has been added on the shaft carrying cam #1. (The commutator was used with magnetic aspect sensors and had no electrical connection with the probe).

Inaccuracies due to variation of motor speed are eliminated by monitoring the speed. A magnetic pick-up is excited by a five-pole generator on the motor shaft giving an ac signal of 500 cycles per second (nominal). Using a small transformer this is added to the output of the instrument at an amplitude of 100 mv (peak-to-peak). Each cycle corresponds to a fixed increment in sweep voltage. A resistor (about 1K ohm)

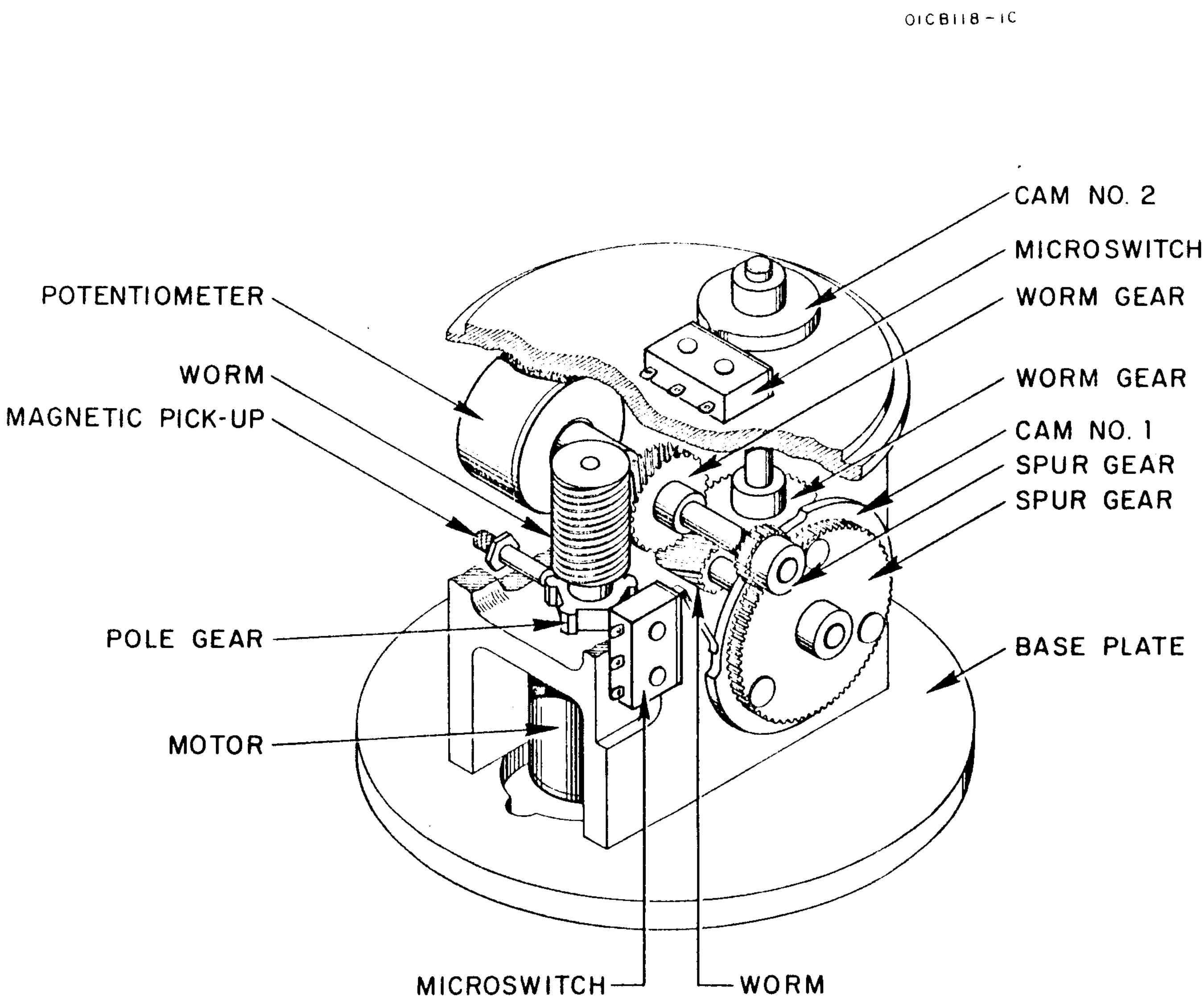


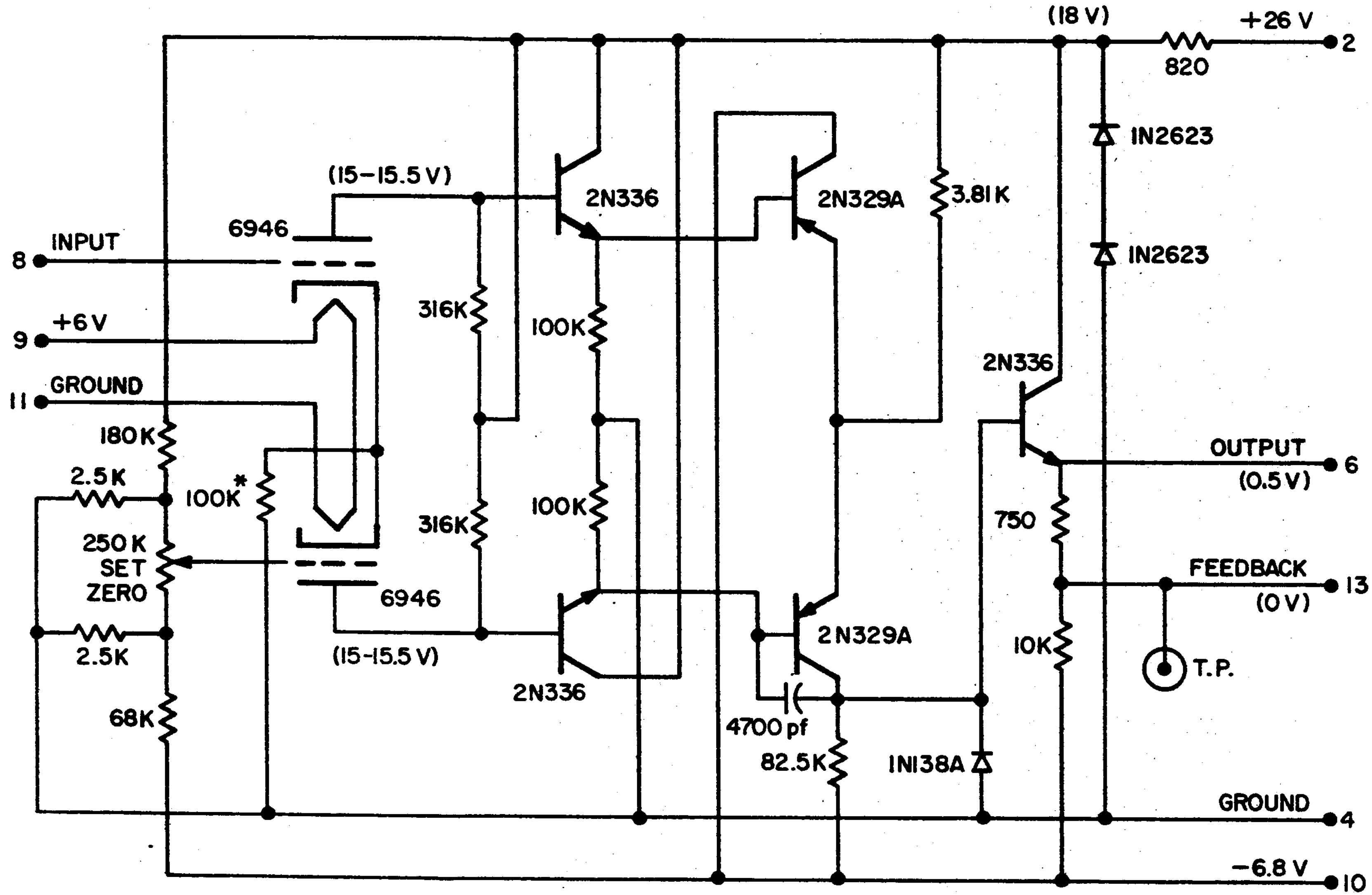
Figure 3-5. Program unit.

is added in series with the sweep potentiometer to give an increment of exactly 0.02 volt per cycle. The presence of these voltage markers on the telemetry record has been found to facilitate date-reduction as well as to increase the accuracy of the measurement. Power for the motor is obtained from the main supply (+28 volt) while the probe voltage is derived from two 2.7 volt mercury cells (Mallory TR-132R). The latter supply is switched on by means of a relay.

3.3 ELECTROMETER

The probe current is measured in the electrometer, Figure 3-6. The tubes in the input stage of this balanced circuit are type 6946 (Sylvania). This is a rugged tube suitable for the severe environment of sounding rockets. Tubes having grid currents less than 10^{-10} amp are selected for use in the electrometer. The electrometer employs 100 percent current feedback. A novel feature is the use of a thyrite resistor (General Electric, Magnetic Materials Division) as the feedback element which results in a compressed scale. The calibration curve of one having a full scale current of about 15 microamp is shown in Figure 3-7. Note that the output of the electrometer is +0.6 volt for zero current at the input of the electrometer. This allows small positive-ion currents to be measured within the limits of 0 and 5 volt prescribed by the standard telemetry systems.

The thyrite resistor alone determines the overall sensitivity of the instrument. With the particular electrode at present in use an electron density of 10^4 cm^3 gives a probe current (at +2.7 volt) of



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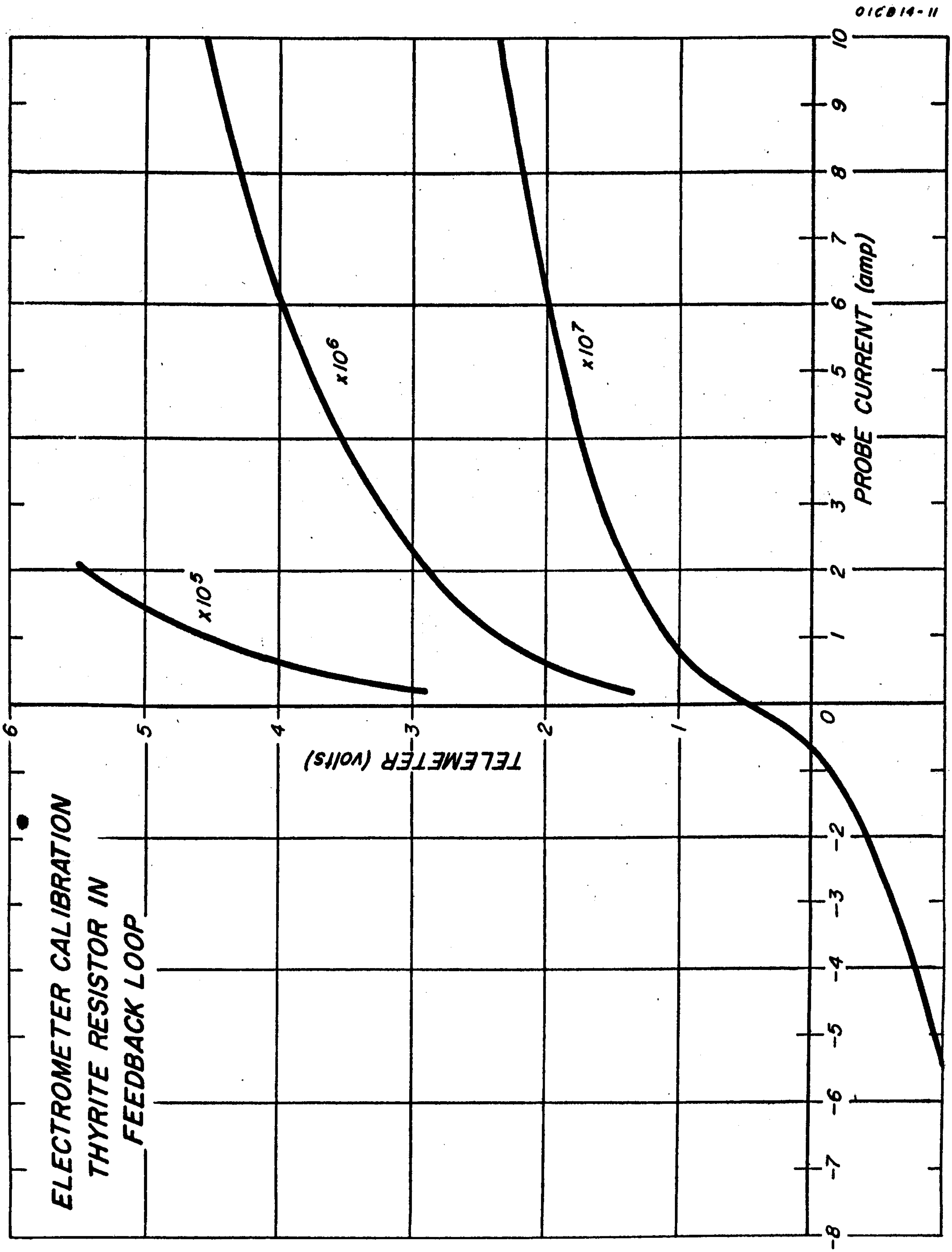
*ADJUST FOR MINIMUM GRID CURRENT AT INPUT

Figure 3-6. **ELECTROMETER**



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ELECTROMETER CALIBRATION
THYRITE RESISTOR IN
FEEDBACK LOOP
TELEMETER (volts)
6
5
4
3
2
1
0
PROBE CURRENT (amp)
10
9
8
7
6
5
4
3
2
1
-2
-3
-4
-5
-6
-7
-8
x 10^5
x 10^6
x 10^7

Figure 3-7.

about 1 microamp. Thus for daytime E region measurements a thyrite giving a current of 30 micoramp (measured at 5 volt) would be selected while at night one giving a current between 5 and 10 microamp (at 5 volt) would be appropriate. Thyrites which show a marked polarity effect (i.e. the magnitude of the current depends on the polarity of the applied voltage) are rejected. Thyrites are also rather temperature sensitive; they are therefore thermally shielded and in addition are calibrated at regular intervals during the flight.

Power for the instrument is obtained from main supply (200 milliamp at +28 volt). In addition the electrometer required a negative supply (1 milliamp at -6.8 volt) which can conveniently be obtained from mercury cells.

3.4 SPECIAL NOTES

The payload housing and rocket motor casing form the second electrode of the bi-polar system. Any voltages developed across portions of the external surface must be carefully considered to avoid interfering with the operation of the probe. One precaution that has been adopted is to disconnect all signals from the umbilical connector using relays within the payload.

A second possible problem concerns rocket gas which could conceivably disturb the ionosphere in the vicinity of the electrode. Trouble from this cause is avoided by sealing the payload with O-rings at the nose tip and providing vent holes toward the rear: four holes, 0.75 in. diameter equally spaced on the circumference. Venting also permits the inclusion in the payload of an altitude switch. This is used for arming a door release mechanism (when used) and in determining trajectory.[(3-1)]

A further precaution which is observed is to limit the power of the telemetry transmitter. It has been found on two occasions that rf breakdown at the antennas supresses the probe current; the vehicle becomes a few volts negative with respect to the plasma potential. Using quadraloop antennas seen in Figure 3-1 with a transmitter developing 5 watts (at 231.4 Mc/sec) breakdown occurred intermittently between 55 and 80 km. No breakdown has been observed at the normal power of 2 watts.

3.5 DATA REDUCTION

The telemetered signal is always tape recorded at two independent ground stations. At the same time a real-time record is obtained at a chart speed of 10 in./sec and a sensitivity of 1 in./volt. This high-speed record is used to obtained electron temperatures. A slow-speed record is also prepared, generally by play-back of the tape, but sometimes in real-time, at a chart speed of 0.25 in./sec and a sensitivity of 1 in./volt. For this record the normal bandwidth of the telemetry channel is reduced to about 100 cycles per second. This eliminates the small ac signal which at the slow speed would merely broaden the trace.

The slow-speed record immediately shows the electron density profile. An example is given in Figure 3-8 which was obtained about one hour before dawn. The record on descent was photographically reversed

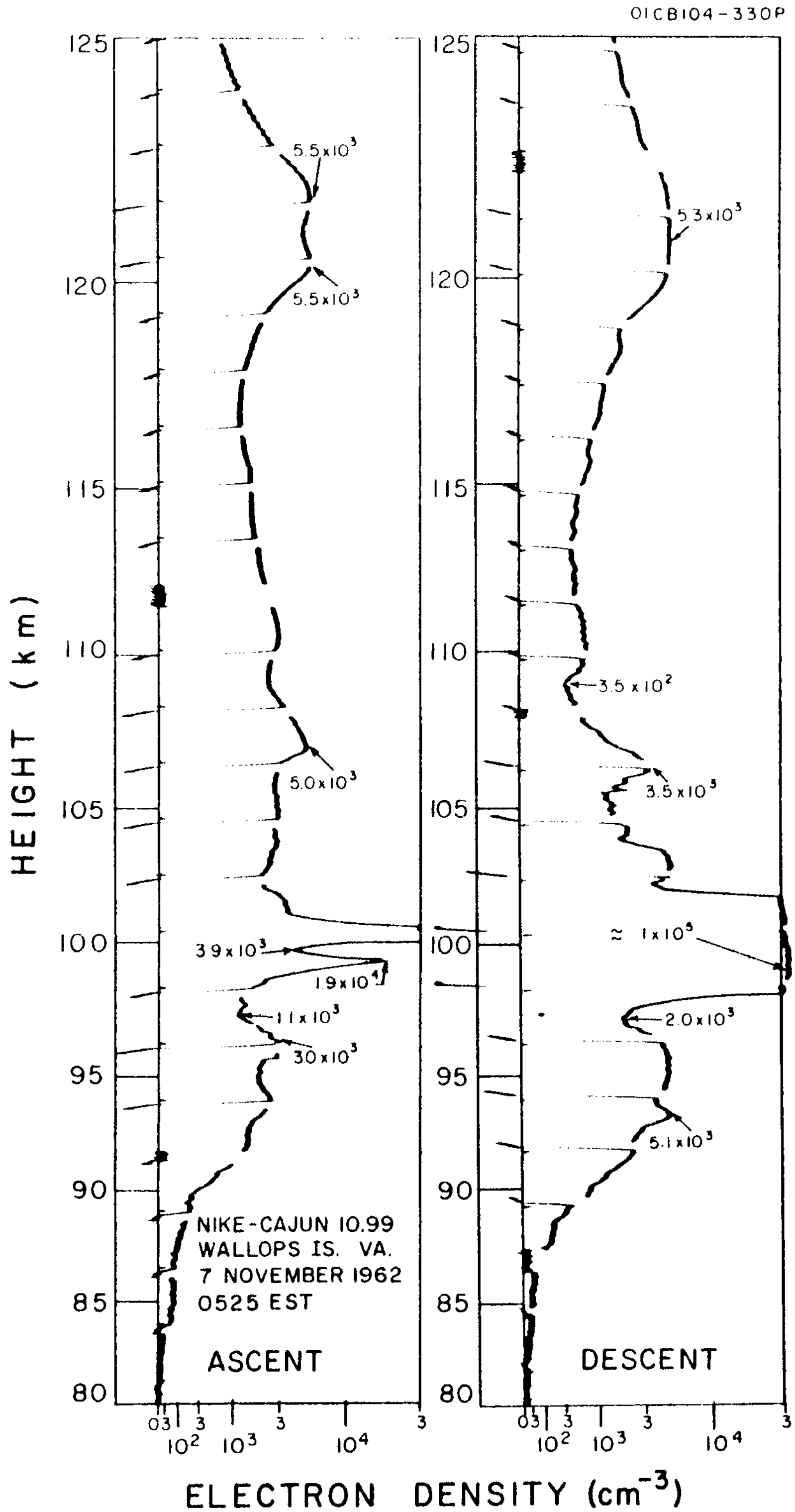

Figure 3-8. Sections of telemetry record showing electron density profile, 7 November 1962, 0525 EST.

for easier comparison with the corresponding portion on ascent. The height scale is obtained directly from radar data. The electron density scale is obtained from the pre-flight or in-flight calibration using a scaling factor obtained from daytime measurements when the absolute value electron density at the peak of the E layer may be obtained from a local ionosonde. The scaling factor used in this case is 1.1×10^{-6} amp equivalent to $1.0 \times 10^{4}\ cm^{-3}$.

The reduction of the data to obtain electron temperature is rather tedious. Individual sweeps of probe voltage must first be measured on the high-speed chart record and a graph prepared of current against voltage. The part of the graph representing collection of positive ions is extrapolated as shown in Figure 3-9 and subtracted from the total probe current to give electron current. This is then plotted on a conventional semi-log plot as shown in Figure 3-10. The slope of the linear part of this semi-log plot gives the electron temperature directly. In principle the absolute value of electron density can also be obtained from this plot by identifying the point at which the probe is at the potential of the plasma; this is normally taken to be the upper limit of the linear portion of the plot. In practice it is difficult to identifying the point accurately due to the gradual curvature of the graph. It is found, in addition, that the absolute values obtained in this way are significantly lower than theory indicates. The discrepancy has not yet been adequately explained and it is recommended that this method of analysis not be used to obtain electron density.

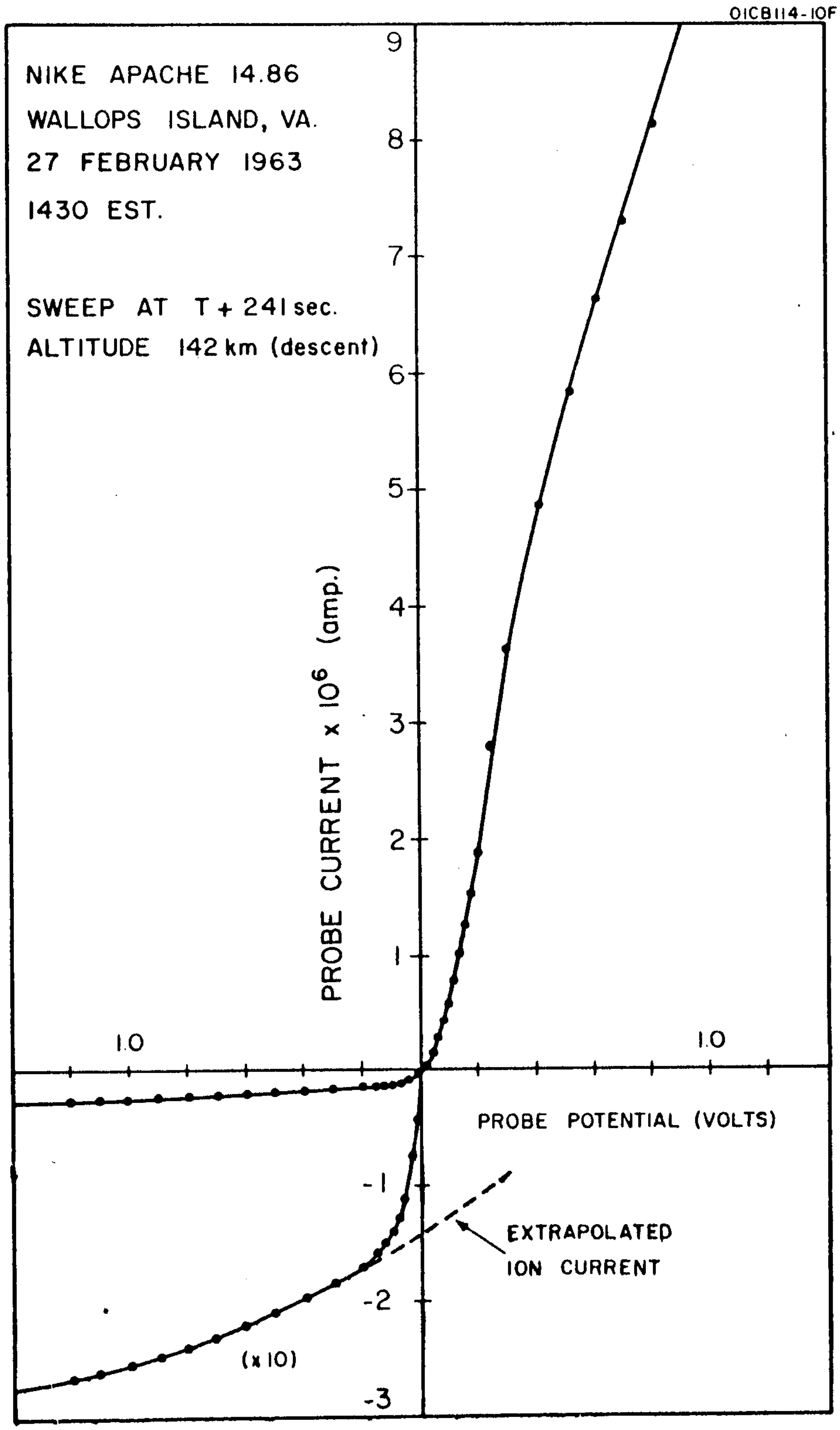

Figure 3-9. Current-voltage characteristic.

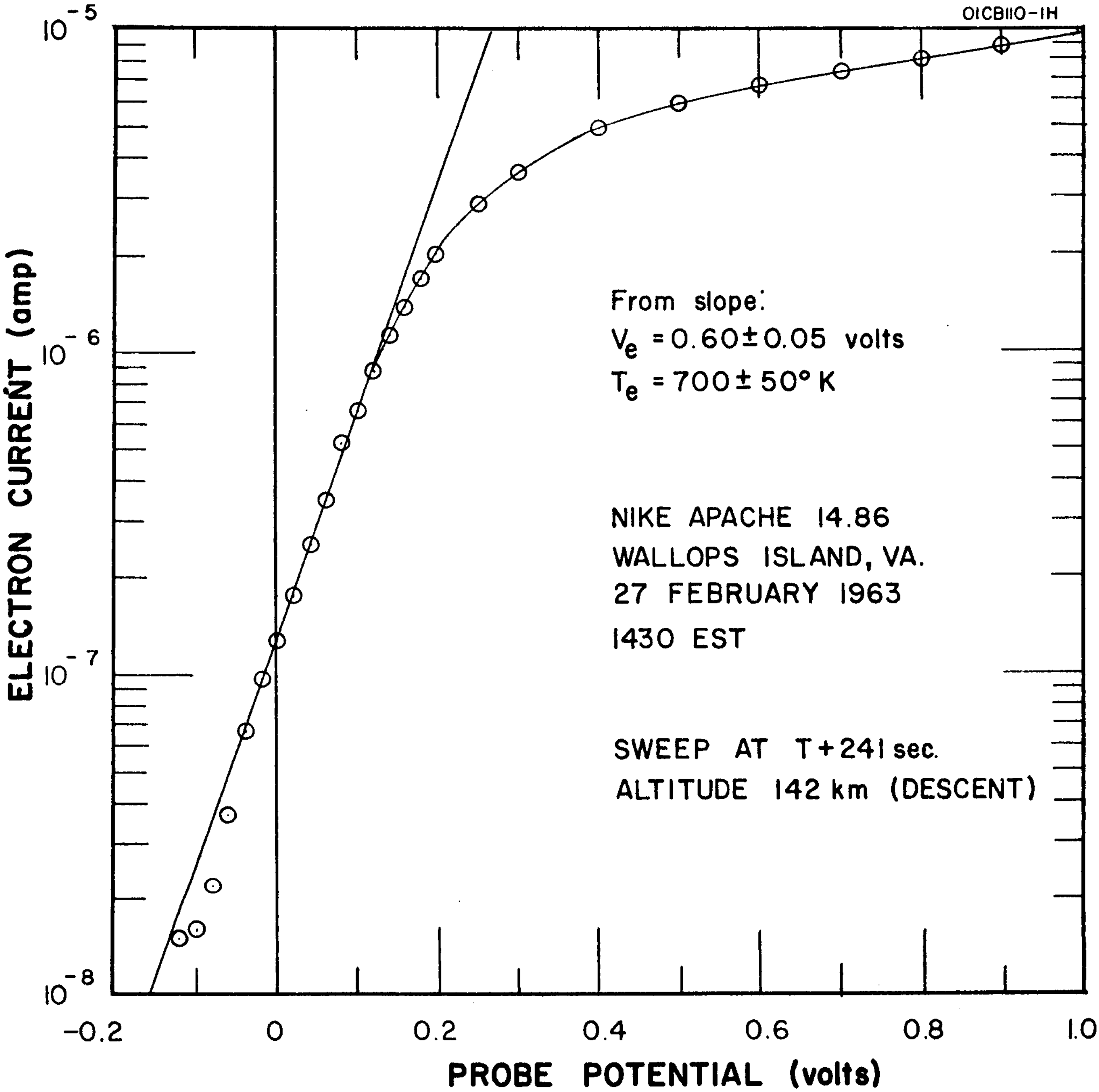

Figure 3-10. Semi-log plot of electron current vs probe potential.

SECTION 4

CONCLUSION

The D.C. probe is an extremely valuable instrument for sounding rockets in the ionosphere. It is very simple in construction, requiring no structural changes in a standard payload housing, and consequently is highly reliable. The greatest advantage of the instrument as it has been developed is the ability to resolve fine structure in the ionosphere. It shows up most strikingly the steep gradients typical of Sporadic E layers but has also revealed many other irregularities of the electron density profile. It appears that the irregularities are characteristic of the ionosphere up to 90 km during the day and up to 120 km at night.

The most significant deviation from Langmuir probe theory which has been encountered concerns the actual value of the electron random current density. The observations indicate values that are lower than the theoretical values by a factor approaching an order of magnitude. Some uncertainty is introduced by the difficulty of identifying exactly the point at plasma potential but this is not enough to account for the low electron current. It is believed that the explanation of the discrepancy can be attributed to the effect of the earth's magnetic field. This point is by no means cleared up and, pending further evidence, either experimental or theoretical, the probe is being used in an empirical manner. The measurement of electron temperature is remarkably independent of such factors as electrode geometry and the geomagnetic field and the technique is used with confidence.

The lowest height to which the Langmuir probe mode of operation is valid has not been established definitely. The high gas density and low electron density below 90 km invalidates the simple probe theory in the D region but there is no clear indication in the actual measurements where the height limit is to be placed. In fact acceptable profiles of electron density down to 50 km are obtained by ignoring the restrictions and applying Langmuir probe theory. The significance of the D region in radio communication, particularly under conditions of high absorption (radio blackout), make the D.C. probe an important instrument for use in the lowest region of the ionosphere and further investigation of its use is indicated.

APPENDIX A

THE ASYMMETRICAL BI-POLAR PROBE

Consider an asymmetrical bi-polar probe consisting of two electrodes of unequal surface area between which a potential may be applied and the resulting current measured. It is assumed that (1) the electron velocity distribution is Maxwellian and can be represented by the temperature T and (2) the sheath thickness is small compared with the radius of curvature of the electrodes, so that the current saturates for accelerating potentials.

Initially, with both electrodes at the same potential, the system assumes a negative potential with respect to the plasma, the floating potential, V_f, given by

$$V_f = -(kT_e/e)\log_e (j_e/j_+) \qquad \text{(A-1)}$$

where k is Boltzmann's constant

T_e the equivalent electron temperature

e the electronic charge

j_e the electron random current density

j_+ the positive ion random current density.

A potential V is applied between the electrodes, V being taken to be positive when the smaller (area A_2) is positive with respect to the larger (area A_1). The potentials of the electrodes assume new values V_1 and V_2, where

$$V = V_2 - V_1 \tag{A-2}$$

The electron currents to the electrodes are, for retarding potentials,

$$i_{e1} = A_1 \, j_e \, \exp[eV_1/kT_e] \tag{A-3}$$

$$i_{e2} = A_2 \, j_e \, \exp[eV_2/kT_e] \tag{A-4}$$

where the subscripts 1 and 2 refer to the larger and smaller electrode, respectively.

It is convenient at this point to introduce two parameters: the area ratio:

$$\sigma = A_1/A_2 \tag{A-5}$$

and the voltage ratio:

$$\eta = eV/kT_e \tag{A-6}$$

with appropriate subscripts for V being applied to η. Thus η is the potential V expressed as a multiple of the electron energy in voltage units.

Now the positive ion currents to the two electrodes are independent of V_1 and V_2 and have values

$$i_{+1} = A_1 \, j_+ \tag{A-7}$$

and

$$i_{+2} = A_2 \, j_+ \tag{A-8}$$

The total electron current must be numerically equal to the total positive ion current, that is

$$i_{e1} + i_{e2} = i_{+1} + i_{+2} \tag{A-9}$$

From (A-3) and (A-4):

$$i_{e1}/i_{e2} = (A_1/A_2)\ \exp[e(V_1 - V_2)/kT_e] \tag{A-10}$$

that is

$$i_{e1}/i_{e2} = \sigma\ \exp[-\eta] \tag{A-11}$$

and from (A-7) and (A-8):

$$i_{+1}/i_{+2} = \sigma \tag{A-12}$$

Finally the probe current i is given by

$$i = i_{+1} - i_{e1} \tag{A-13}$$

Therefore, using (A-9), (A-11), (A-12) and (A-13), we find:

$$i/i_{+1} = \left[\frac{\exp(\eta) - 1}{\exp(\eta) + \sigma}\right] \tag{A-14}$$

This is the mathematical formulation of the current-voltage characteristic of an asymmetrical bi-polar probe having an area ratio $\sigma(\geq 1)$. It is plotted in Figure A-1 for values of σ of 1, 10, 100, and 1000. The curve for the symmetrical bi-polar probe ($\sigma = 1$) is point symmetric about the origin (only the positive half is shown). For values of σ greater than 100, the curves become point symmetric about the point

$$i/i_{+1} = 0.5 \tag{A-15}$$

and

$$\eta = \log_e\ (2 + \sigma). \tag{A-16}$$

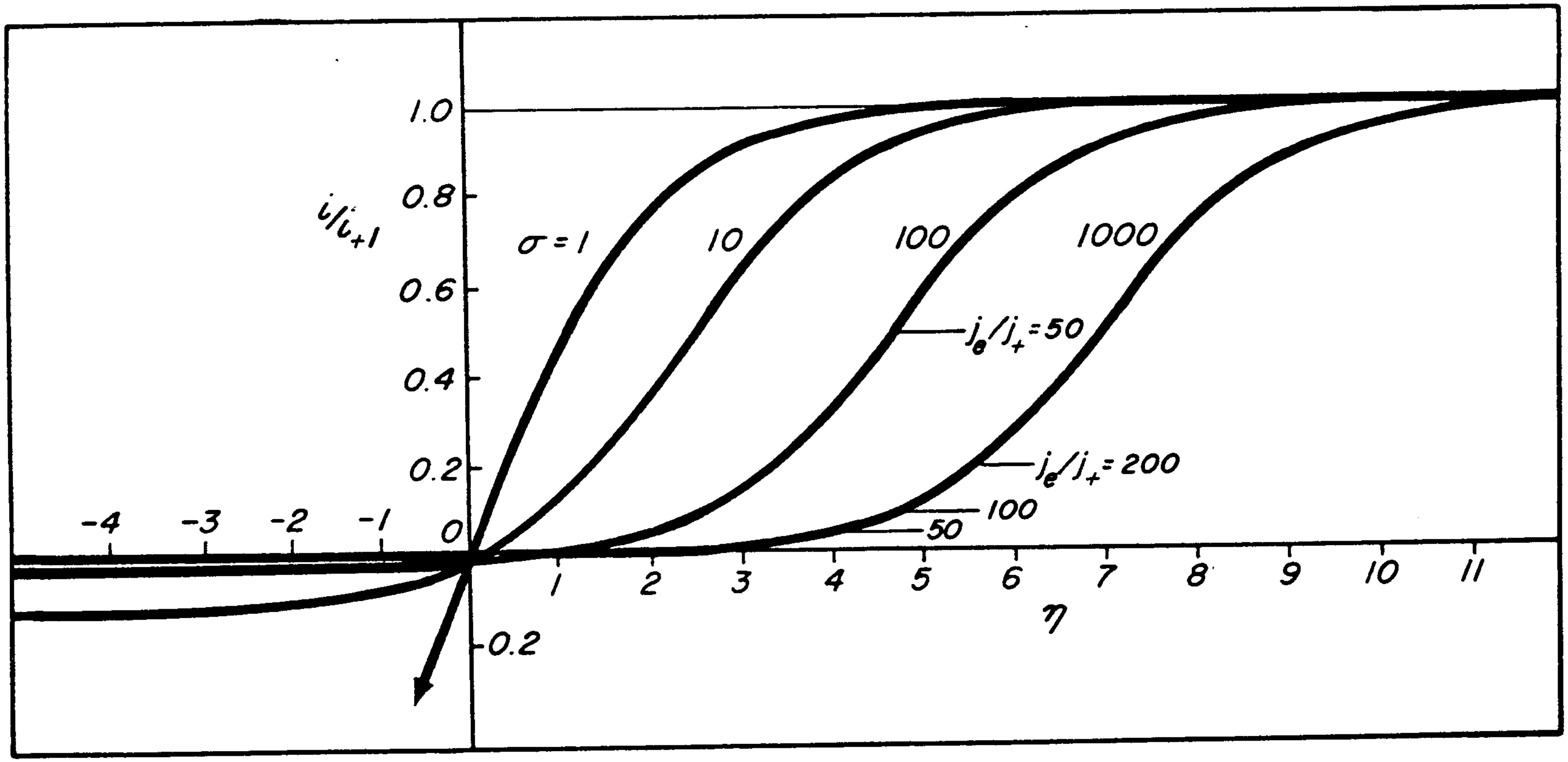

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Figure A-1. Current-Voltage Characteristics for Four Values of Area Ratio.

We must now introduce the restriction that the above analysis is valid only for retarding potentials on the electrodes. For accelerating potentials, the electron current is limited to the random current density. Now the potentials of the two electrodes, η_1 and η_2, are given by

$$\exp\ (-\eta_1) = (j_e/j_+)\ \frac{\sigma + \exp(\eta)}{\sigma + 1} \tag{A-17}$$

and

$$\exp\ (-\eta_2) = (j_e/j_+)\ \frac{\sigma\ \exp(-\eta) + 1}{\sigma + 1} \tag{A-18}$$

Saturation occurs when the smaller electrode reaches space potential ($\eta_2 = 0$) at a value of η given by

$$\exp(\eta) = \frac{\sigma(j_e/j_+)}{\sigma + 1 - (j_e/j_+)} \tag{A-19}$$

and a value of i given by

$$i/i_{+1} = (j_e/j_+ - 1)/\sigma \tag{A-20}$$

If $\sigma < (j_e/j_+ - 1)$, no electron current saturation occurs.

The point at which electron current saturation occurs is thus determined by the area ratio σ and the random current density ratio j_e/j_+. The short horizontal lines in Figure A-1 indicate electron current saturation. In the ionosphere the value of j_e/j_+ is computed to be about 200.

The floating potential $\eta_f (=eV_f/kT_e)$ is from equation (A-1),

$$\exp(\eta_f) = j_e/j_+ \tag{A-21}$$

and therefore, as might be expected, for very large σ ($\gg j_e/j_+$) the smaller electrode saturates when η is equal to the floating potential. In other words, for sufficiently large σ the smaller electrode is essentially a single probe and the larger electrode maintains a constant potential equal to the floating potential. We may determine how large σ must be for such a simplification to be made; it evidently must be several times the value of j_e/j_+. In Figure A-2 the curves of Figure A-1 are replotted on semi-log paper in the manner used on deriving electron temperature. On this plot the ordinate is

$$\Delta i/i_{+1} = (i + i_{+2})/i_{+1} \tag{A-22}$$

The single Langmuir probe is characterized by a linear plot on semi-log paper. It is seen in Figure A-1 that for all values of σ the plots are very close to linear for $\Delta i/i_{+1} \leqslant 0.1$. Now electron saturation occurs at $\Delta i/i_{+1} = (j_e/j_+)/\sigma$. Therefore the condition that the asymmetrical bi-polar probe may be analyzed as a single probe is

$$\sigma \geqslant 10\ (j_e/j_+). \tag{A-23}$$

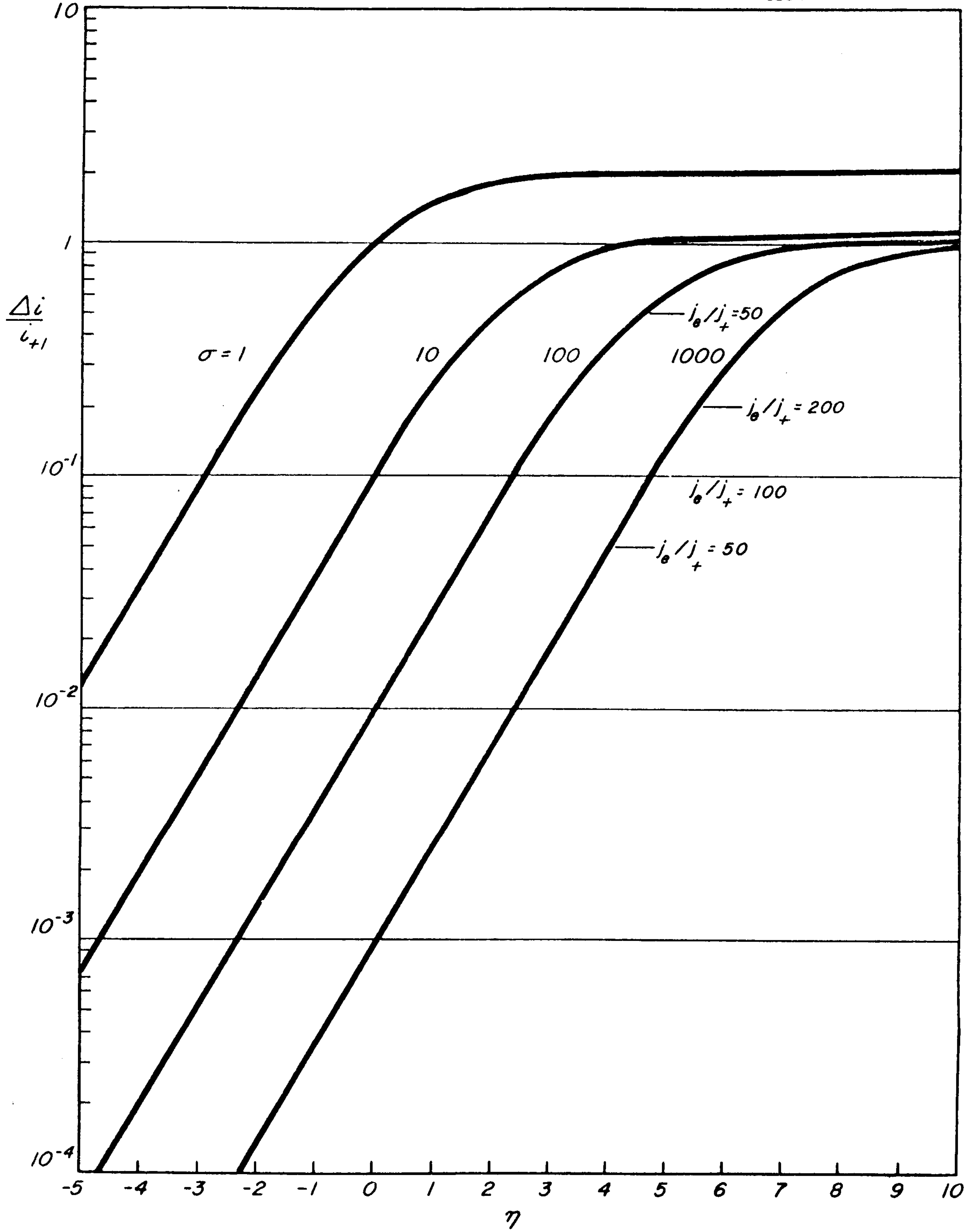

Figure A-2. Semi-log Plot of Current-Voltage Characteristics for Bi-polar Probes.

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